Interactions of Particles with Flow Structures in Turbulent Channel Flows

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Outline

- Flow Simulations (DNS)
  - Geometry and boundary condition
  - Governing equations
- Particle Simulations
  - Governing equations
- Results
  - Evolution of near wall coherent structure
  - Time and space evolutions
- Conclusions
Methodology: Fluid Flow

Direct Numerical Simulation (DNS)

❖ Pseudo-Spectral code

❖ Solves the Navier-Stokes equations

\[
\frac{\partial \mathbf{u}_f}{\partial t} + \mathbf{u}_f \cdot \nabla \mathbf{u}_f = -\frac{1}{\rho_f} \nabla P + \frac{1}{\text{Re}_L} \nabla^2 \mathbf{u}_f
\]

\[
\nabla \cdot \mathbf{u}_f = 0
\]

❖ Streamwise and spanwise velocities are expanded by Fourier series

❖ The normalized velocities are expanded by Chebyshev series
Methodology: Fluid Flow

Boundary Conditions:
\[
\begin{align*}
    u^+ &= 0, \quad y = \pm H^+/2 \\
    u^+(x^+ + \lambda^+_x, y^+, z^+ + \lambda^+_z, t^+) &= u^+(x^+, y^+, z^+, t^+),
\end{align*}
\]

Gridding
\[
\begin{align*}
    nx &= 128, ny = 129, nz = 64 \\
    &1,056,768\text{ cells}
\end{align*}
\]

Chebyshev series
\[
y_i^+ = \frac{H^+}{2} \cos\left(\frac{\pi i}{M}\right), \quad 0 \leq i \leq M
\]

\[
\begin{align*}
    \lambda^+_x &= 1260 \\
    \lambda^+_z &= 630 \\
    \frac{H^+}{2} &= 125 - 590 \\
    y \quad \text{Upper Wall} \\
    z \quad \text{Lower Wall} \\
    x \quad \text{Mean Flow}
\end{align*}
\]
Eulerian-Lagrangian Method

Wall units:
\[
X^+ = \frac{X u^*}{\nu}
\]
\[
t^+ = \frac{tu^2}{\nu}
\]
\[
u^+ = \frac{u}{u^*}
\]

\[
\frac{d u_p^+}{dt^+} = C_D F_D^+ + F_l^+ + n^+(t^+)
\]

Drag force  Lift Force  Brownian motion

Particle equation of motion:
\[
\frac{dx_p^+}{dt^+} = u_p^+
\]

Drag coefficient:
\[
CD = \begin{cases} 
1 + 0.1875Re_p & \text{Re} \leq 0.01 \\
1 + 0.1315Re_p^{0.82+0.0217 \ln(Re_p)} & 0.01 \leq Re_p \leq 20
\end{cases}
\]
Coherent Wall Vortices

- Counter rotating vertices
- Elongated along the streamwise direction
- 100 wall units distance spacing
- Burst and inrush events
Normal Velocity and Vorticity Contours

At a Cross Section

Along the channel

Time Variations

Vorticity Contours
Velocity Contours on Planes Parallel to Walls

**Time Variations**

- **U Velocity**
- **V Velocity**
- **W Velocity**
Concentration Profiles

\[ d_p = 10 \text{ nm} \]

\[ d_p = 20 \text{ \(\mu\)m} \]
Velocity Profiles

- Fluid
- • dp=80 μm
- • dp=50 μm
- • dp=1 μm
Streamwise Direction

Streamwise Direction

Space Variations

\[ dp = 60 \, \mu m \]

\[ dp = 30 \, \mu m \]

\[ dp = 1 \, \mu m \]

\[ dp = 10 \, \mu m \]

\[ dp = 60 \, \mu m \]
Preferential Concentration of 20 µm particles

Normalwise direction

Streamwise direction

Spanwise direction

Space Variations
X-Velocity Contours with 30 µm particles

Normalwise direction

Spanwise direction
Y-Velocity Contours with 30 µm Particles

Normalwise direction

Spanwise direction
\( \tau_p^+ = 10 \)
$\frac{1}{p^+} = 10$
Mean Flow Direction

Deposition Pattern

\[ d = 25 \mu m \]
Pattern of Deposition on the Lower Wall

Dp=80 µm

Dp=60 µm
Pattern of Deposition on the Lower Wall

\[ D_p = 30 \mu m \]

\[ D_p = 10 \text{ nm} \]
Iso-Q & Iso-Vorticity Contours
Conclusions

• The coherent near-wall turbulent structures were visualized.
• The turbophoresis effects on particle concentration and velocity profiles were observed.
• For inertial particles with $\tau^+ = 2 - 60$, the turbulence near-wall eddies control the near-wall preferential concentration and the particle deposition process.
• For larger or smaller particles, the preferential concentration patterns become smeared.
Questions